Diamond Electronics
Amplifier to Detector

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Overview

- Why Diamond?
- Electron transport
  - Electrons vs X-rays – What can we learn?
  - Responsivity & gain
  - Charge collection distance (CCD) & Trapping
  - White beam test
- Diamond-metal interface
- Defects and spatial uniformity
- Future experiments

Why Diamond?

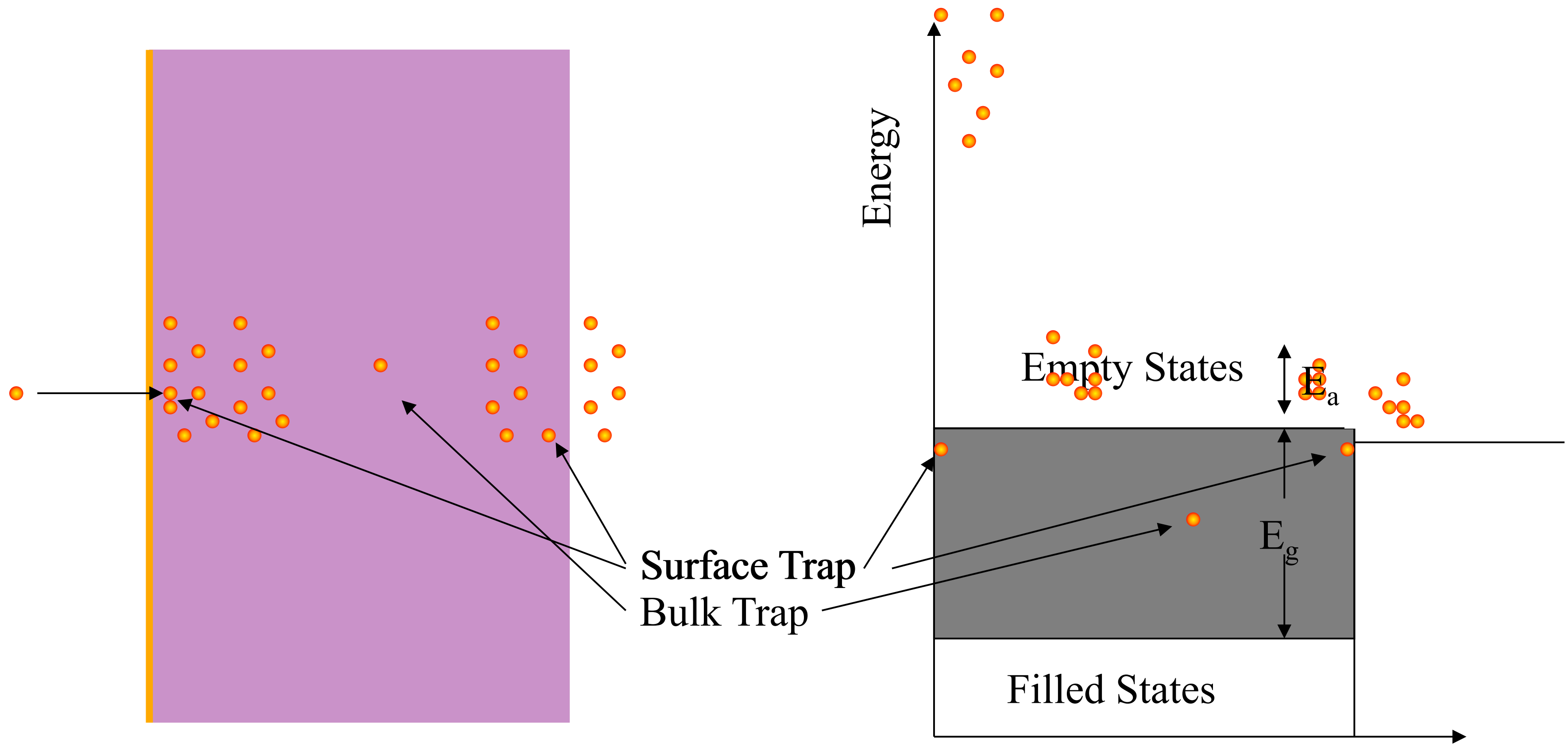
Electron Amplifier

- Radiation hard
- Fast (high mobility)
- High thermal conductivity
- Robust ohmic contacts
- Negative electron affinity
  - Easy (Hydrogen)
  - Robust (Covalent Bond)
  - Controllable?

Detector

- Radiation hard
- Fast
- High thermal conductivity
- Robust ohmic contacts
- Solar blind
- Low leakage
- Low absorption
  - Transmission devices (beam monitors)

Electron Transport in Diamond
Electron Generated, Amplifier Case



Primary electrons lose energy in metal layer via e^--e^- scattering (density and thickness)

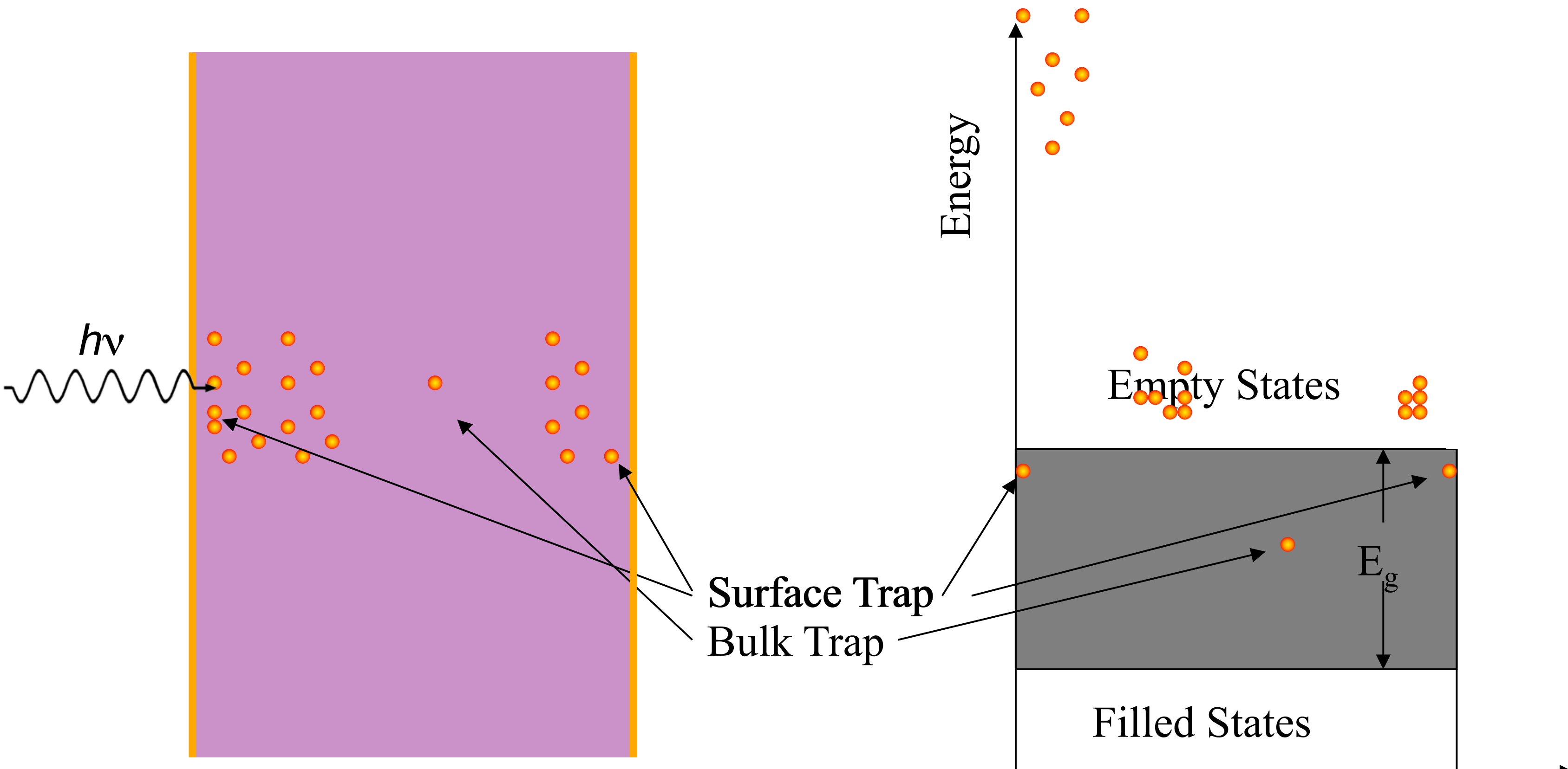
Stop in <1um of diamond lose remaining energy via e^--e^- scattering

Excite e^- into conduction band

Some e^- lost to recombination at metal interface (probability based on drift vs diffusion)

Electrons may be trapped near surface

Electron Transport in Diamond
Photon Generated, Detector Case

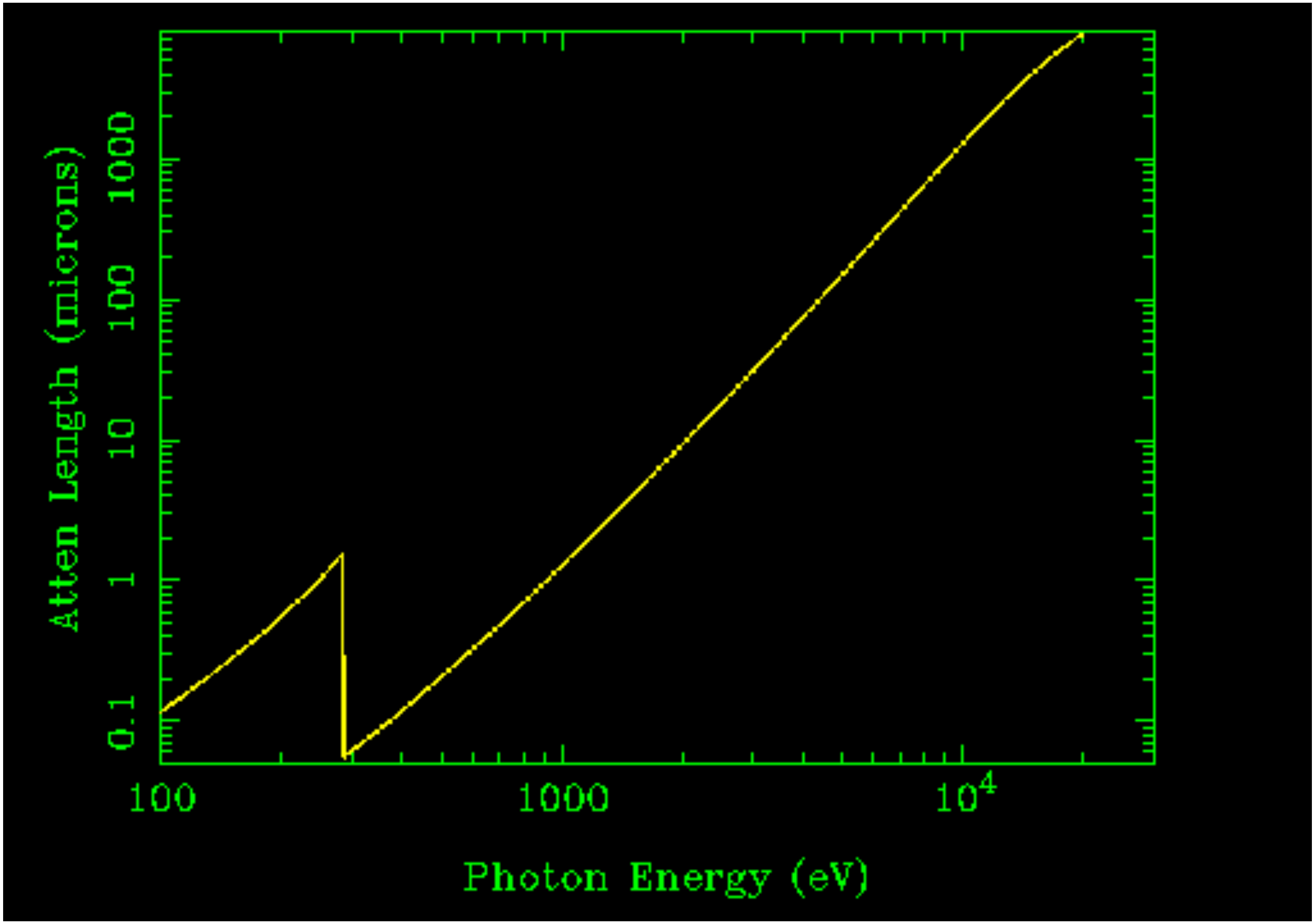


Some photons lost to absorption in metal layer (atomic absorption edges)
Bias determines which carrier crosses diamond for soft x-rays
Some carriers trapped
Photons produce energetic electrons via photoelectric absorption
Other surface metallized
For harder x-rays (>3 keV) both carriers participate
Most drift through
Penetration depth strong function of photon energy
Some e⁻ trapped at surface
Current induced in electrode as soon as carriers begin moving
Carriers lose energy via phonon scattering
Electrons scatter, produce electron-hole pairs
Most will be collected
Eventually, e⁻ reaches the conduction band min, hole reaches valance band max
Trapped carriers modify field
Some e⁻ lost to recombination at metal interface, possibly surface trapping

Why use X-rays?

- Penetration depth is a strong function of energy -> Can differentiate between surface and bulk effects
- Electron energy from photoabsorption is well defined – can accurately measure mean ionization energy W
- Absorption edges allow differentiation of attenuation from metal vs “dead” carbon
- Distinguish between electron and hole effects
- Shorter pulses and higher flux available
- Calibrated diagnostic beamlines available at NSLS

Photon Absorption Length



Responsivity and "Gain"

- In the detector business, the term gain is generally reserved for amplification mechanisms which add energy to the signal in the conversion mechanism (avalanche in a gas detector, for example)
- For the electron "amplifier", this is not the case – the incident electron is losing it's energy, and this energy is converted into carriers, much like a calorimeter
- Similarly, in a photodetector, the energetic electron produced via absorption of an x-ray photon will produce many carriers
- The "responsivity" of a photodetector (in A/W) is given by:

$$S = \frac{1}{w} e^{-t_{window}/\lambda_{window}} \left(1 - e^{-L_{active}/\lambda_{active}}\right)$$

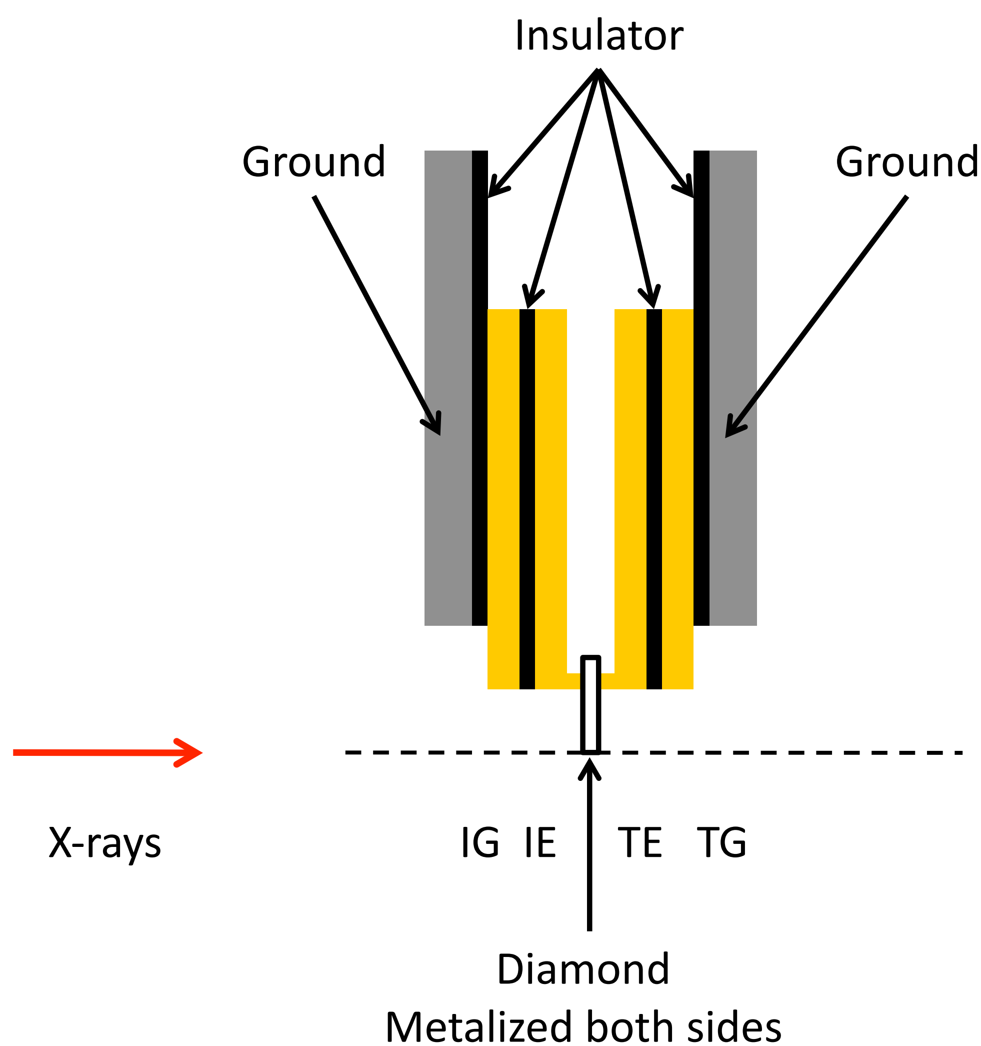
W is the mean ionization energy – the energy required to create an electron-hole pair

Trapping and Pulsed Bias

- Initially, DC bias was used on detector
  - Hole response was much lower than expected, and non-linear with flux
- By pulsing the bias on the detector (using an amplified square wave for bias)
  - Hole response matched the model prediction for bias field greater than 0.1 MV/m -> nearly all charge collected
  - Works for wide range of frequencies (1 Hz to >10kHz) and duty cycles (up to 99%)
  - During off cycle, x-ray illumination generates carriers which drift toward and neutralize trapped charge

Responsivity Measurements

Detector Geometry



4 Addressable Electrodes
IG: Incident Guard
IE: Incident Electrode
TE: Transmission Electrode
TG: Transmission Guard

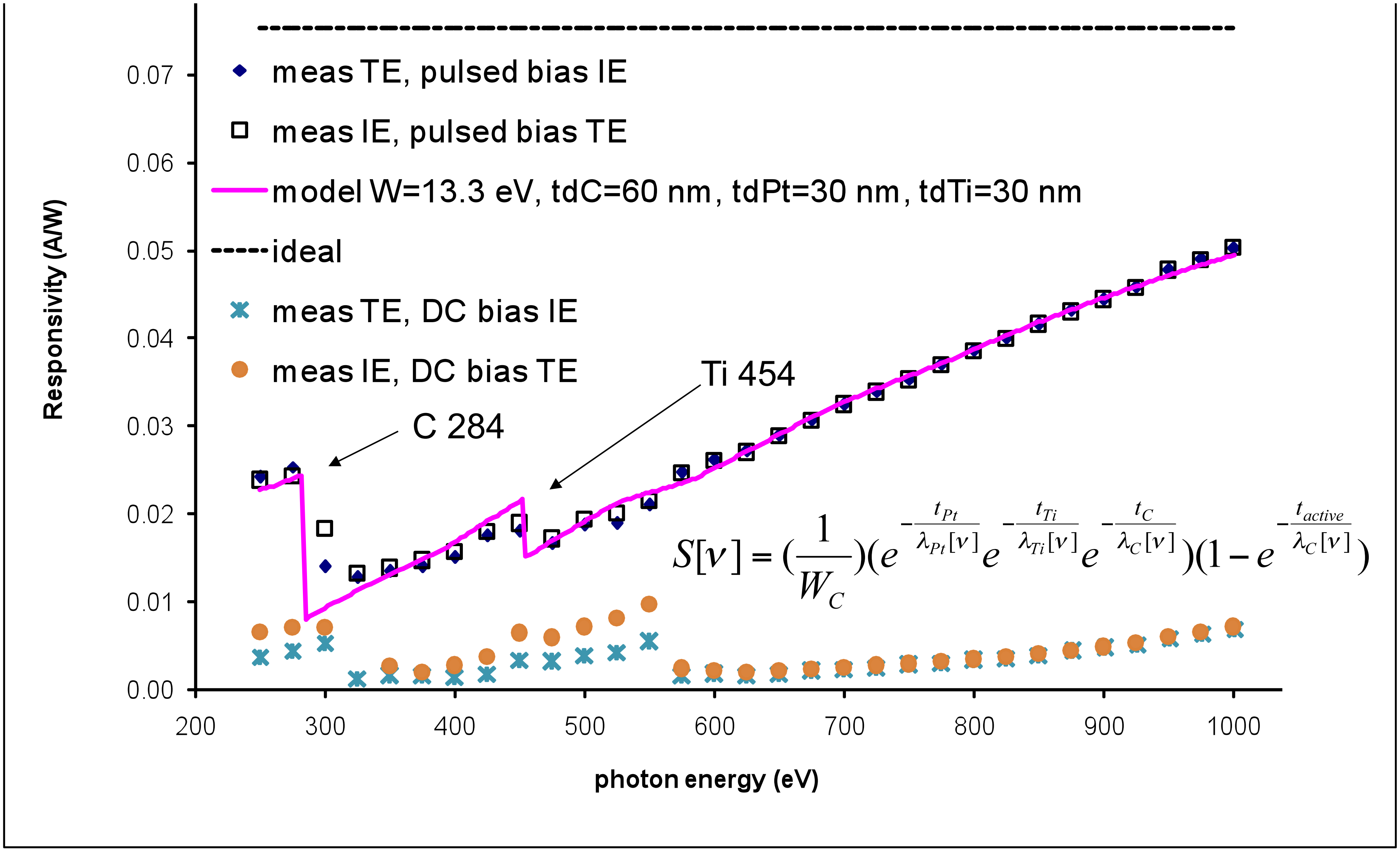
Each can be biased (+ or -) or used for measurement, allowing two hole measurements and two electron measurements

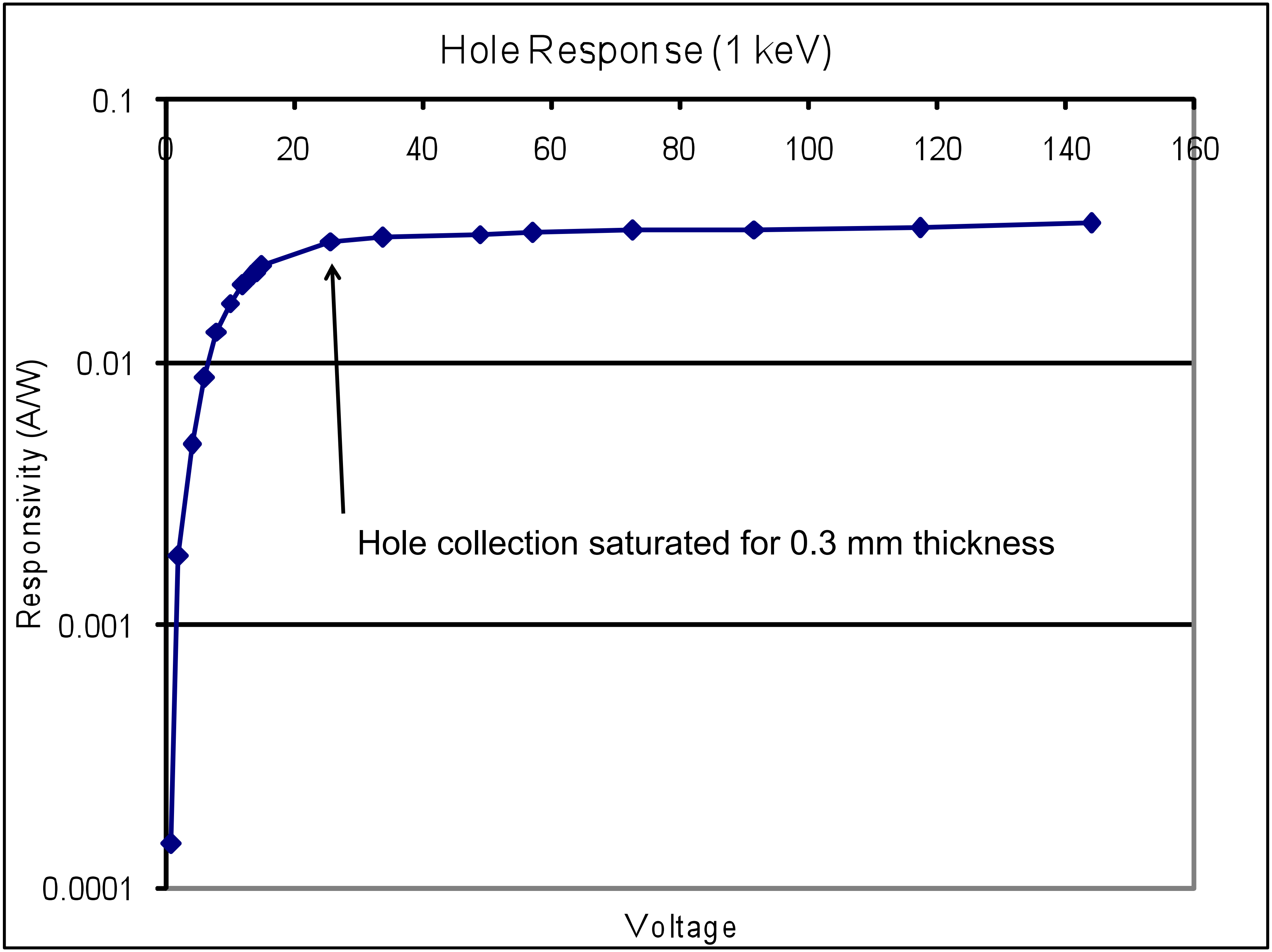
Guards biased to suppress photoemission

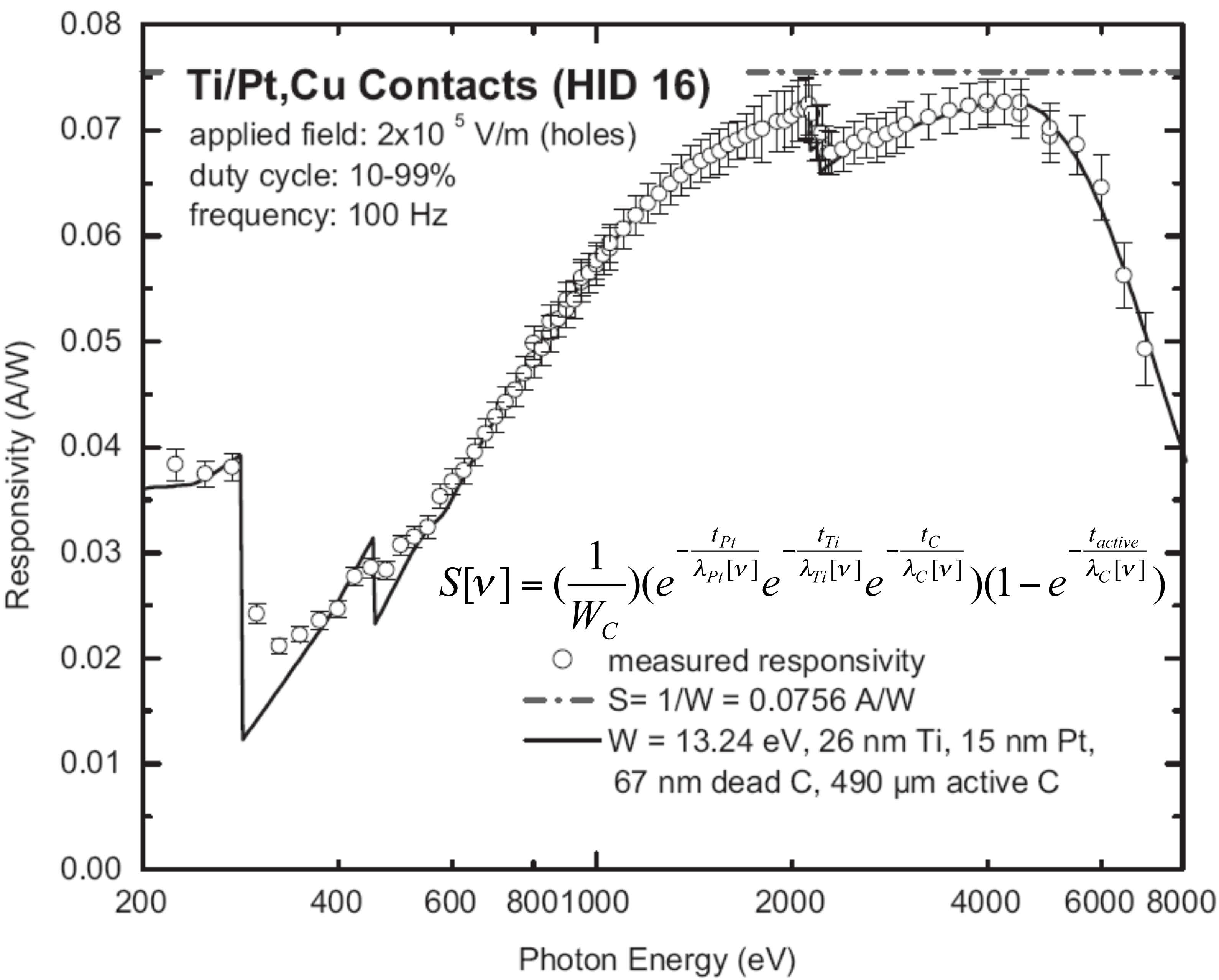
5 single crystal diamonds tested (various metallizations)

Hole Responsivity vs Photon Energy

60V bias



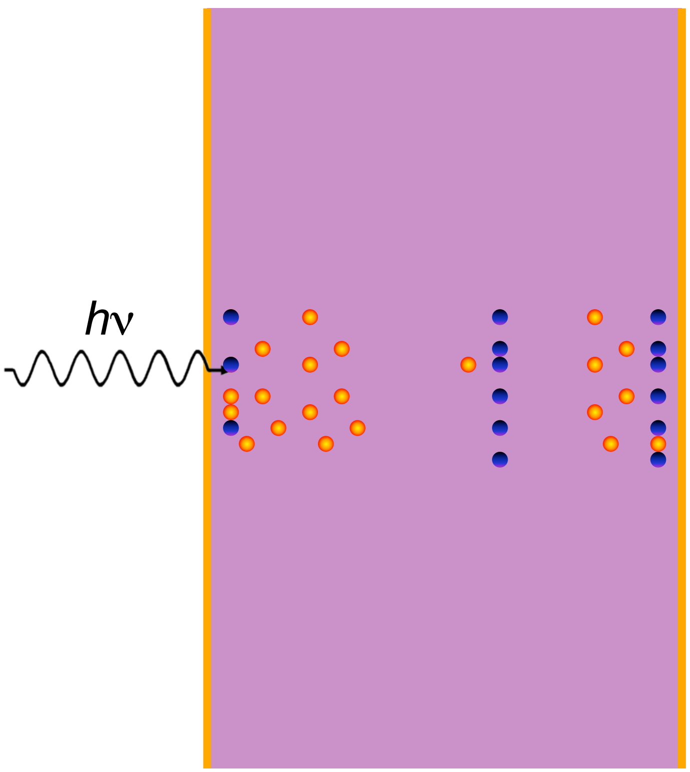

Hole Response (1 keV)
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
120
140
160
Responsivity (A/W)
Voltage
Hole collection saturated for 0.3 mm thickness


Ti/Pt,Cu Contacts (HID 16)
applied field: 2x10 5 V/m (holes)
duty cycle: 10-99%
frequency: 100 Hz
$S[\nu] = (\frac{1}{W_C})(e^{-\frac{t_{Pt}}{\lambda_{Pt}[\nu]}} e^{-\frac{t_{Ti}}{\lambda_{Ti}[\nu]}} e^{-\frac{t_C}{\lambda_C[\nu]}})(1 - e^{-\frac{t_{active}}{\lambda_C[\nu]}})$
measured responsivity
S= 1/W = 0.0756 A/W
W = 13.24 eV, 26 nm Ti, 15 nm Pt,
67 nm dead C, 490 µm active C
Responsivity (A/W)
Photon Energy (eV)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
200
400
600
8001000
2000
4000
6000 8000

What about electrons?

- Electron response depends strongly on type of electrical contacts (more on contacts later)
- For blocking contacts, electrons exhibit significantly more trapping than holes
  - Lower duty cycle of pulsed bias to avoid signal loss
  - Never collect all electrons
- For ohmic (annealed contacts), photoconductive gain is observed
  - Trapped electrons act as effective “doping” of material
  - Boundary conditions require material to be charge neutral
  - Holes are injected from opposite electrode

Photoconductive Gain



Photons produce initial carriers
Electrons drift through diamond
Some electrons are trapped in material
Act as effective p-type doping as long they are trapped

One hole is injected into diamond for each trapped electron, keeping material charge neutral

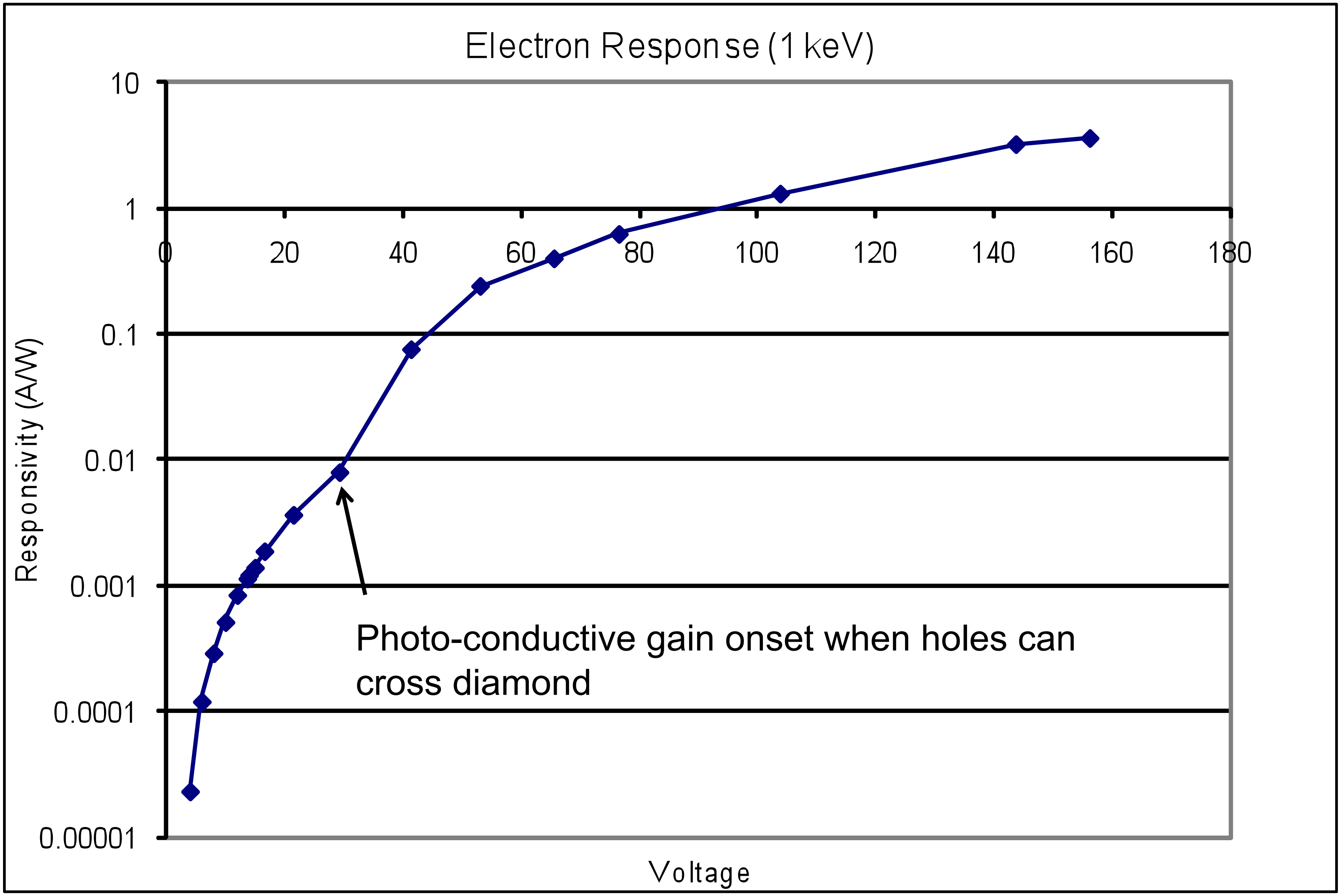
Holes drift through diamond
New holes enter, each time adding current

Process continues until the hole is trapped in the material or the trapped electron is neutralized

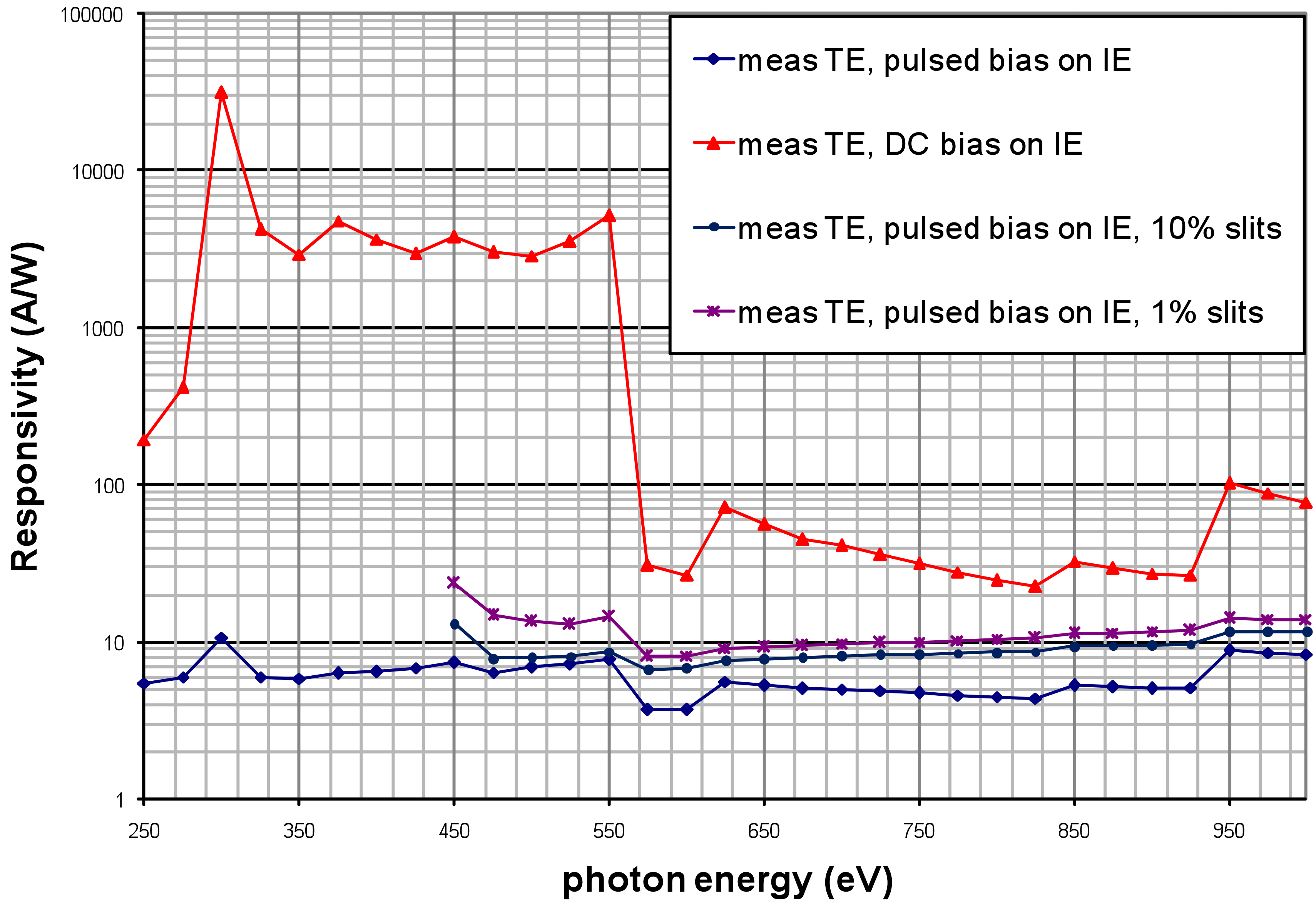
$$Gain = \frac{\tau_{holes}}{t_{holes}}$$

Hole lifetime

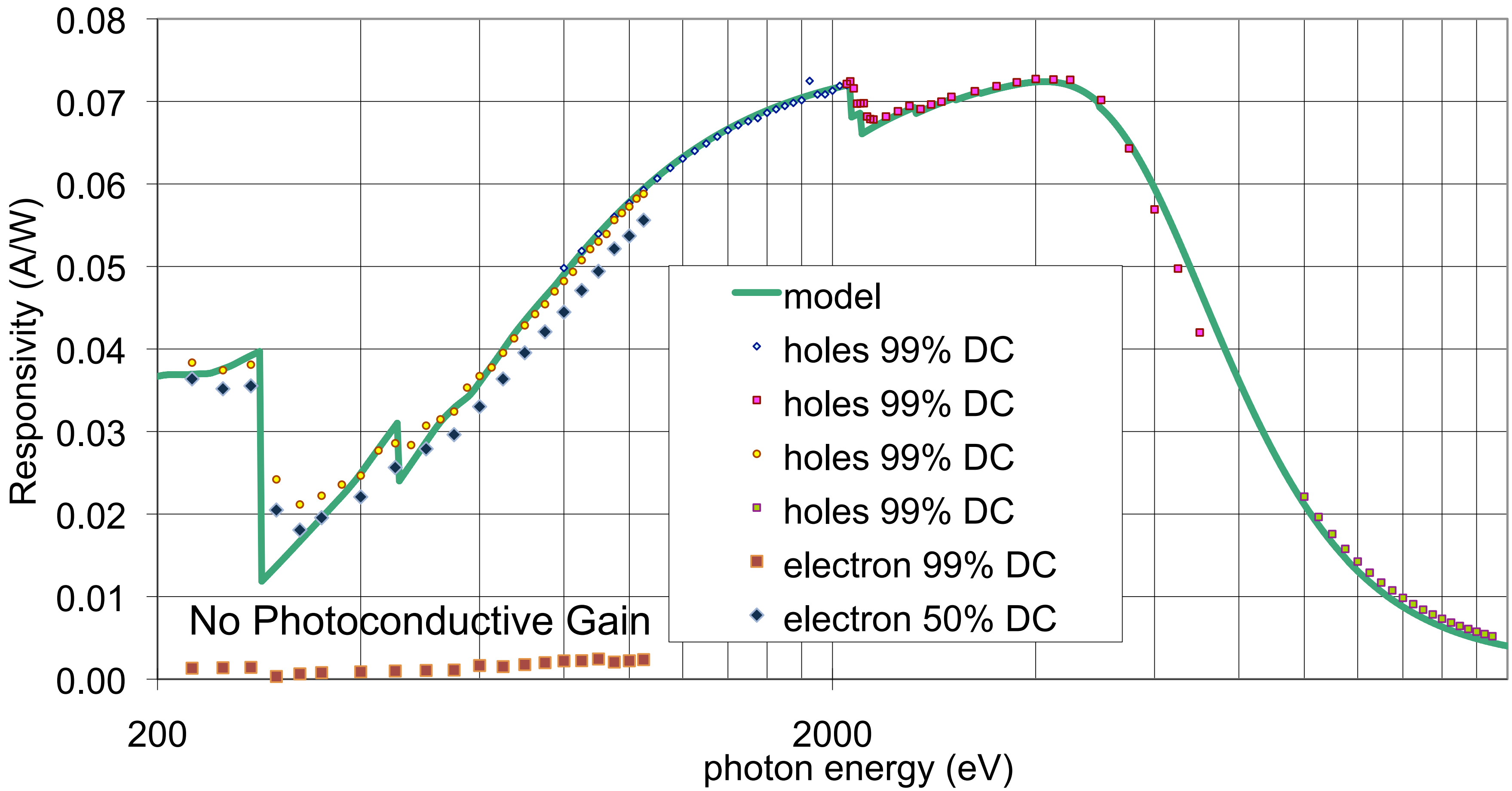
Hole transit time


Electron Response (1 keV)
10
1
0.1
0.01
0.001
0.0001
0.00001
0
20
40
60
80
100
120
140
160
180
Responsivity (A/W)
Voltage
Photo-conductive gain onset when holes can cross diamond

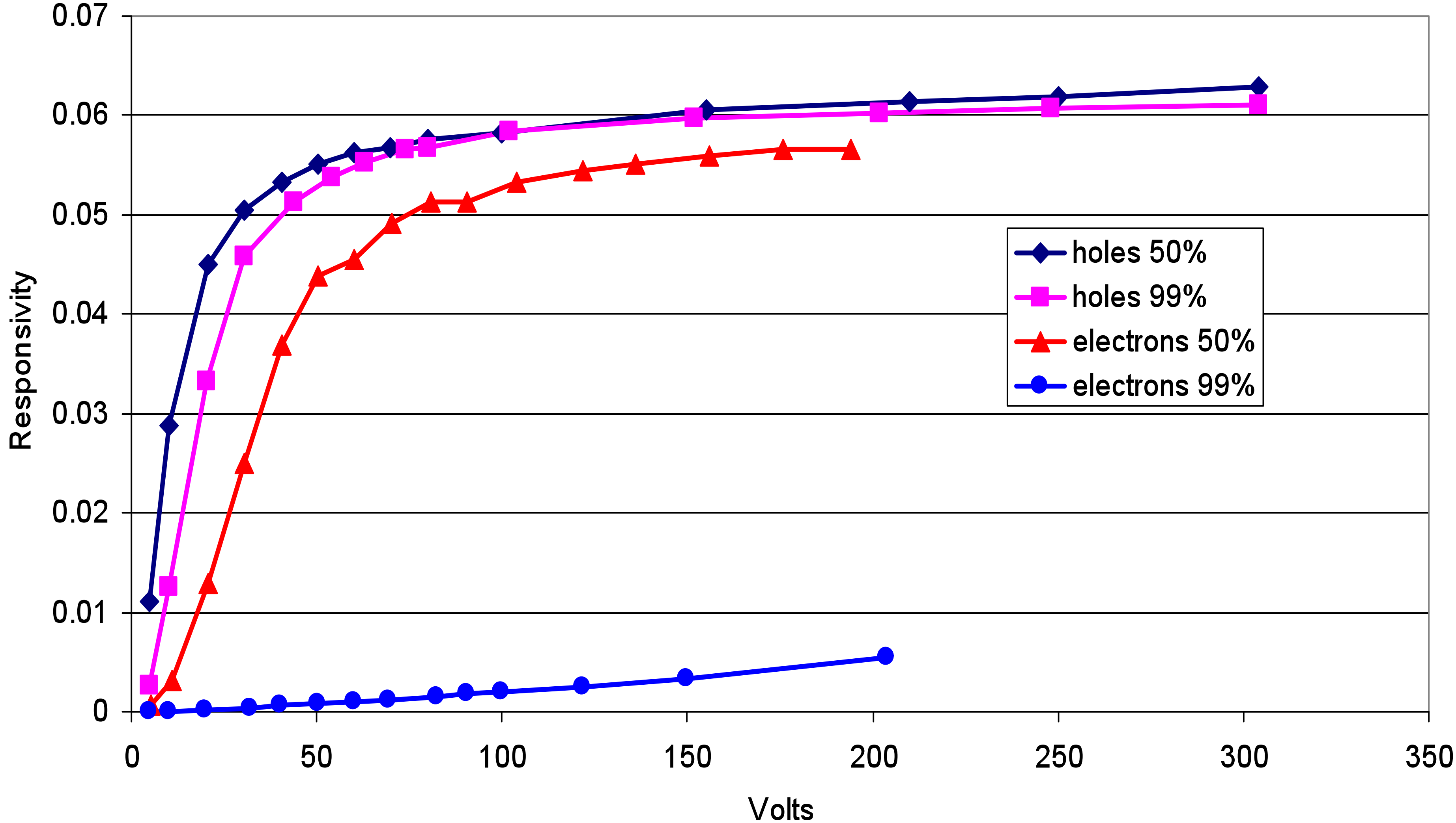
Electron Response, ohmic



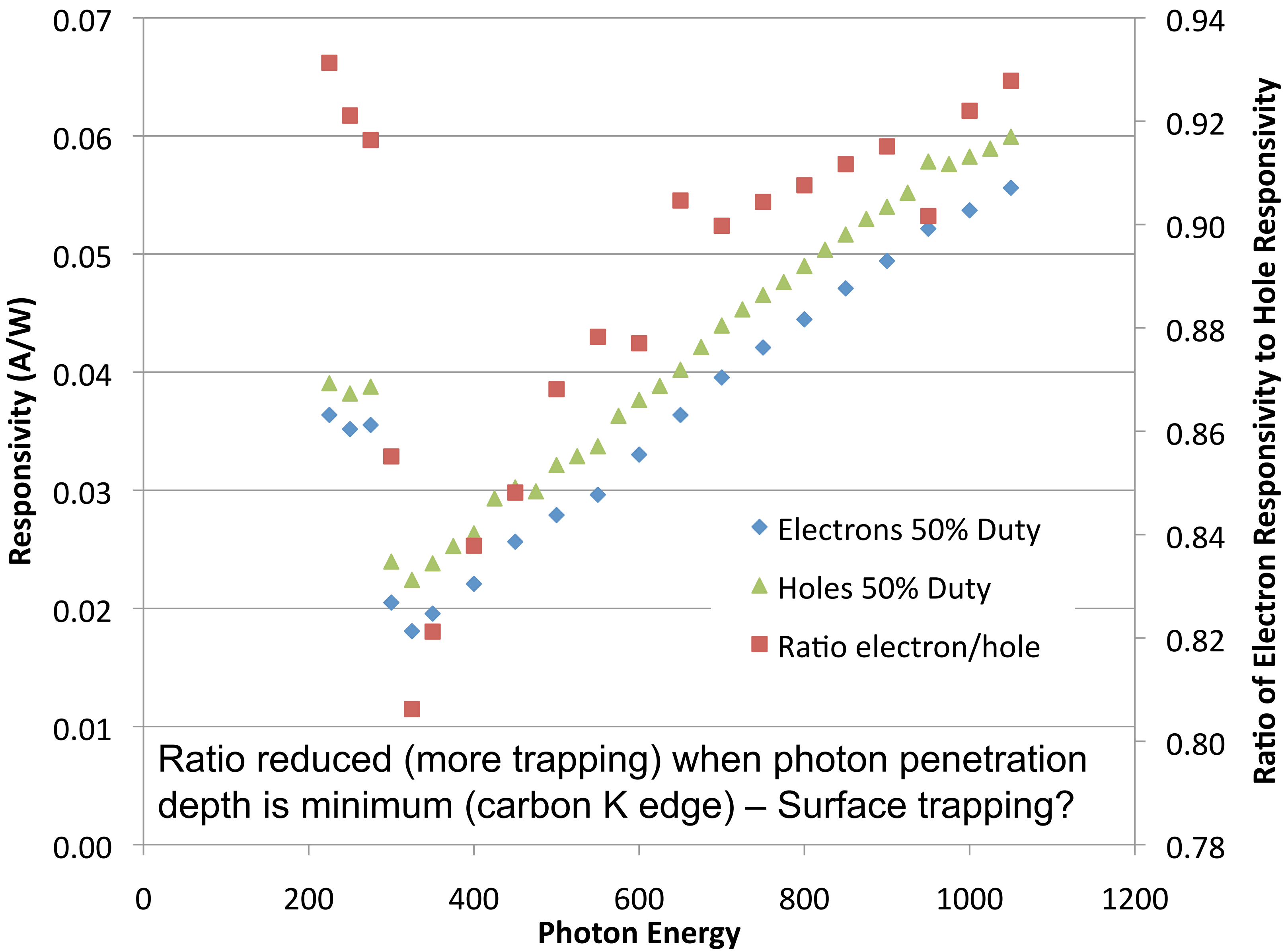
Ti/Pt annealed & Cu, holes, 100V bias
Contacts: one ohmic, one blocking

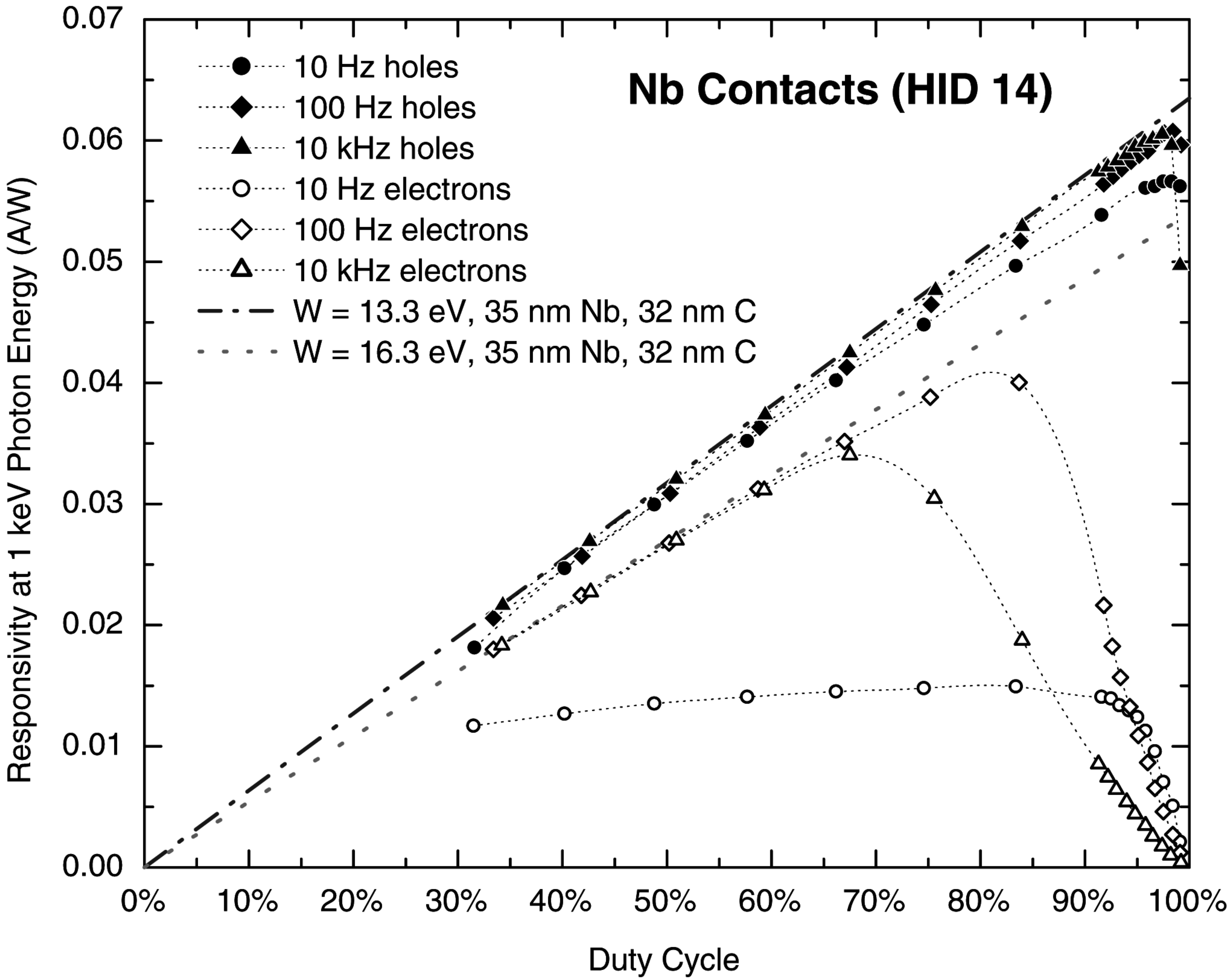


S vs V (Ti/Pt annealed & Cu)



Ratio of Electron to Hole Response



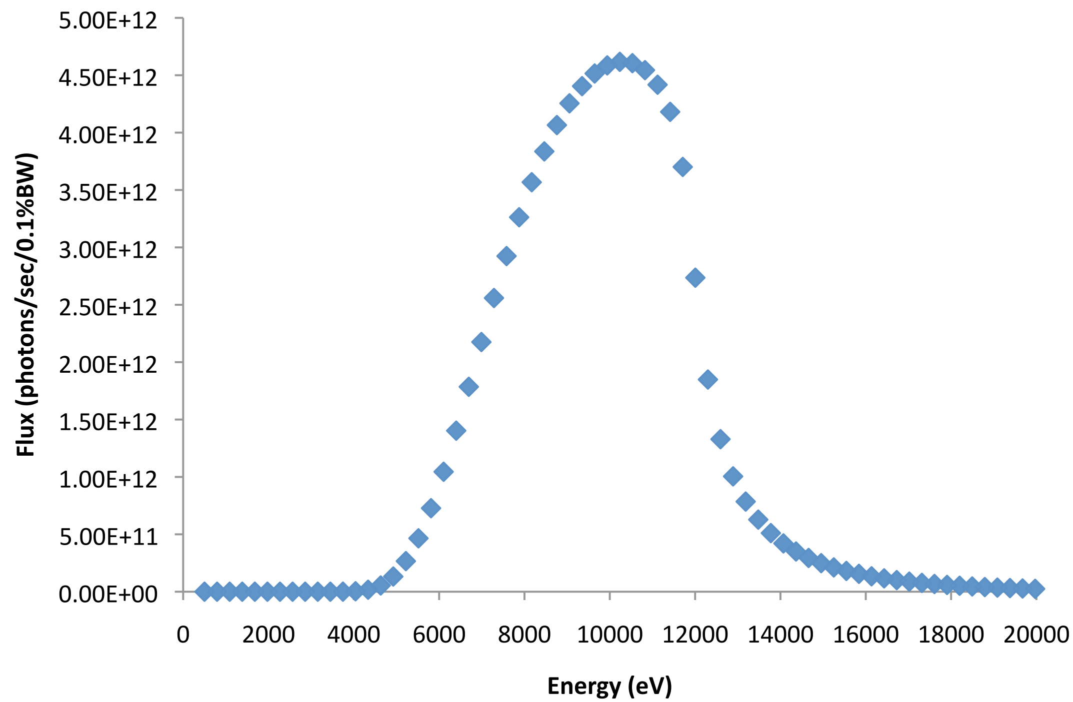

Nb Contacts (HID 14)
10 Hz holes
100 Hz holes
10 kHz holes
10 Hz electrons
100 Hz electrons
10 kHz electrons
W = 13.3 eV, 35 nm Nb, 32 nm C
W = 16.3 eV, 35 nm Nb, 32 nm C
Responsivity at 1 keV Photon Energy (A/W)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Duty Cycle

Responsivity Conclusions

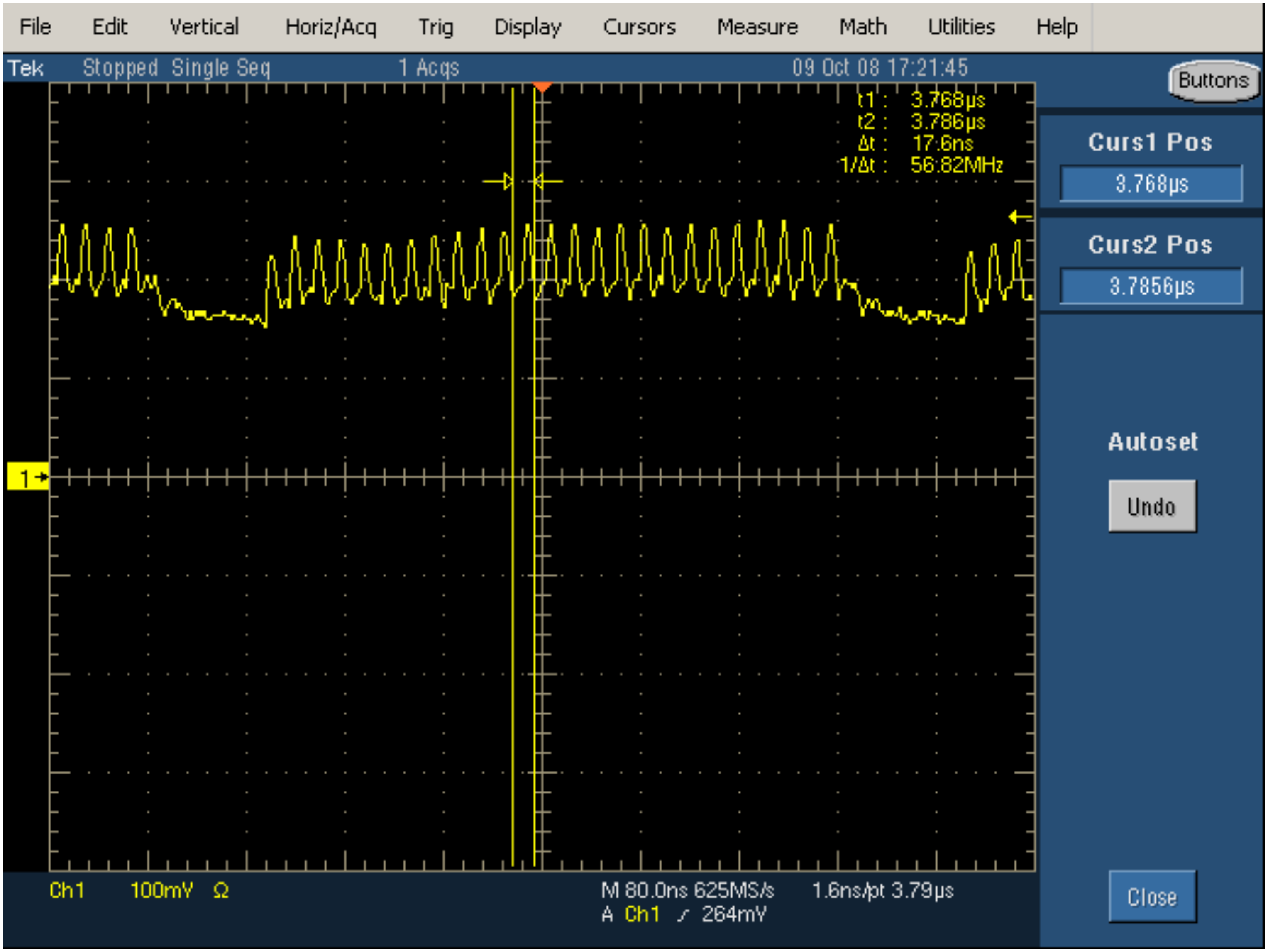
- Holes are the majority carrier in these synthetic diamonds (due to ultra low N content)
- Charge collection for holes is limited only by diffusion of carriers if field is low – for E>0.1 MV/m, all holes collected
- Simple model of Responsivity yield thickness of damaged carbon layer, metal thicknesses
- Electron trapping occurs in bulk diamond; cannot collect all electrons – leads to PC gain w/ two ohmic contacts
- Can sweep trapped charge by irradiating diamond w/o bias

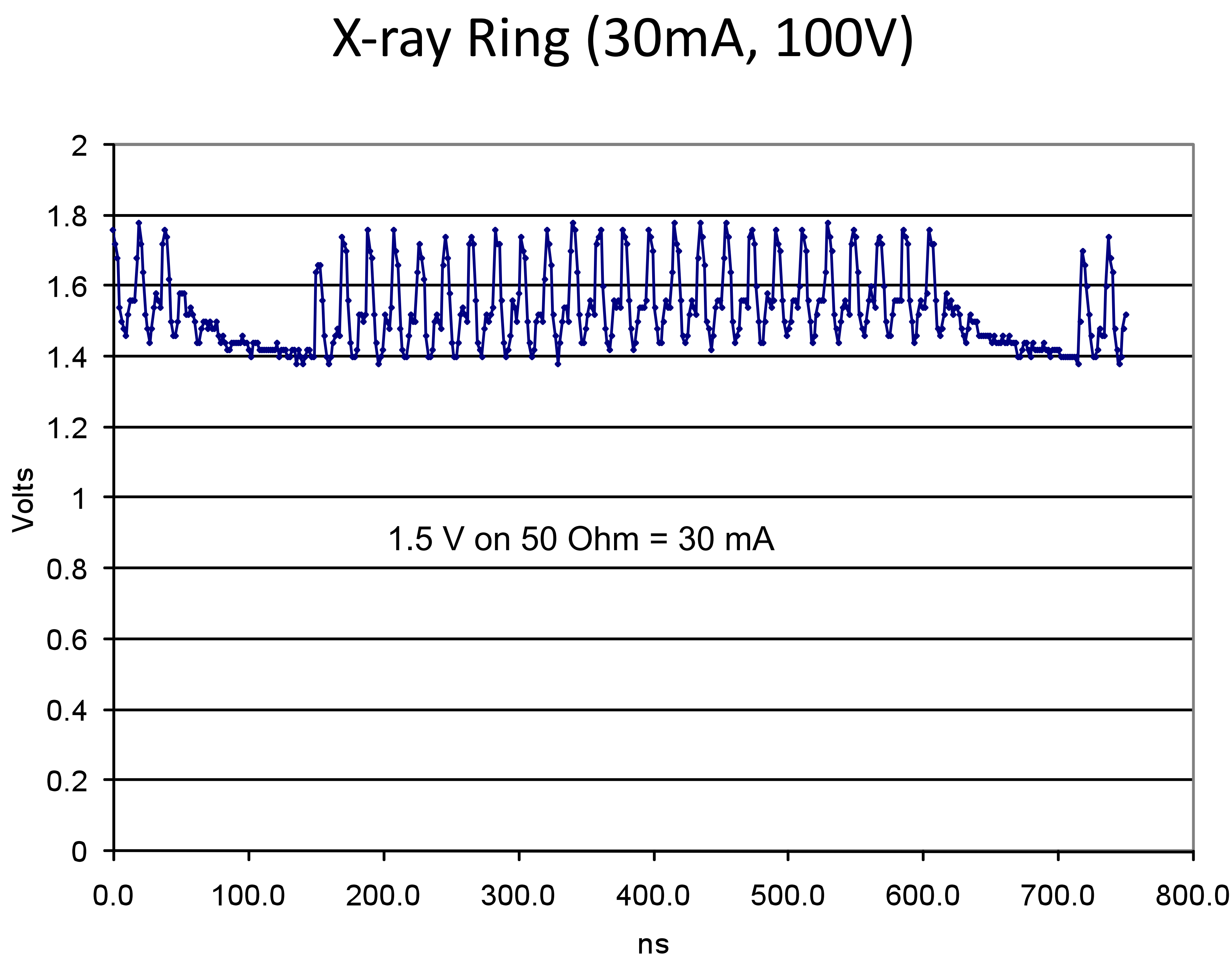
White Beam Test

- Diamond detector used on beam at X28C, with 17W of X-ray power, ranging from 6 keV to 15 keV
- Intercepted ~1/6 of beam
- Generated 30 mA of current through diamond in a 1.6mm diameter area – power supply limited
- **1.5 A/cm^2**
- Can see NSLS ring repetition frequency on detector (~1ns pulses)



X-ray Ring (50 micron Al, 4mA, 100V)



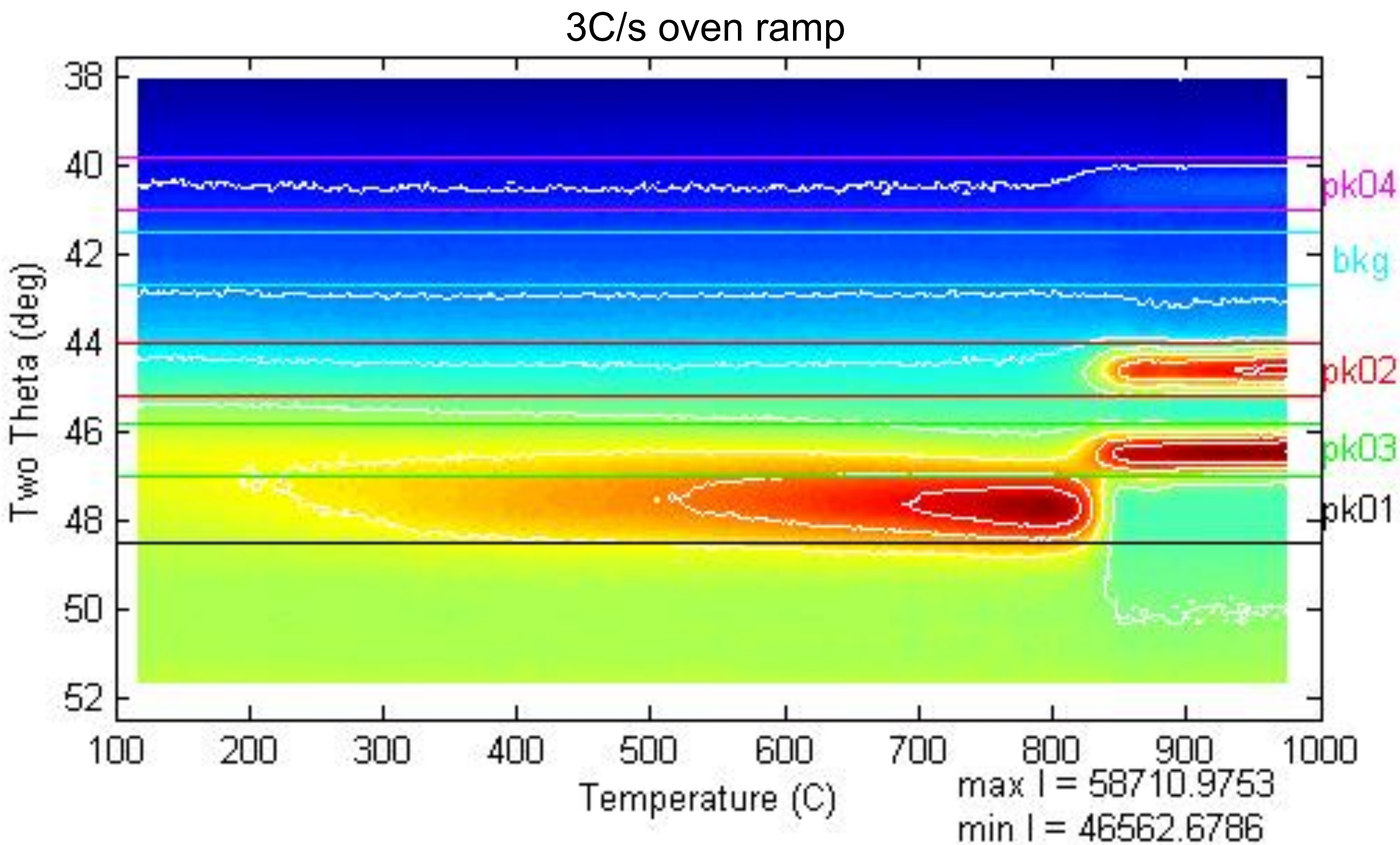


X-ray Ring (30mA, 100V)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Volts
1.5 V on 50 Ohm = 30 mA
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
ns

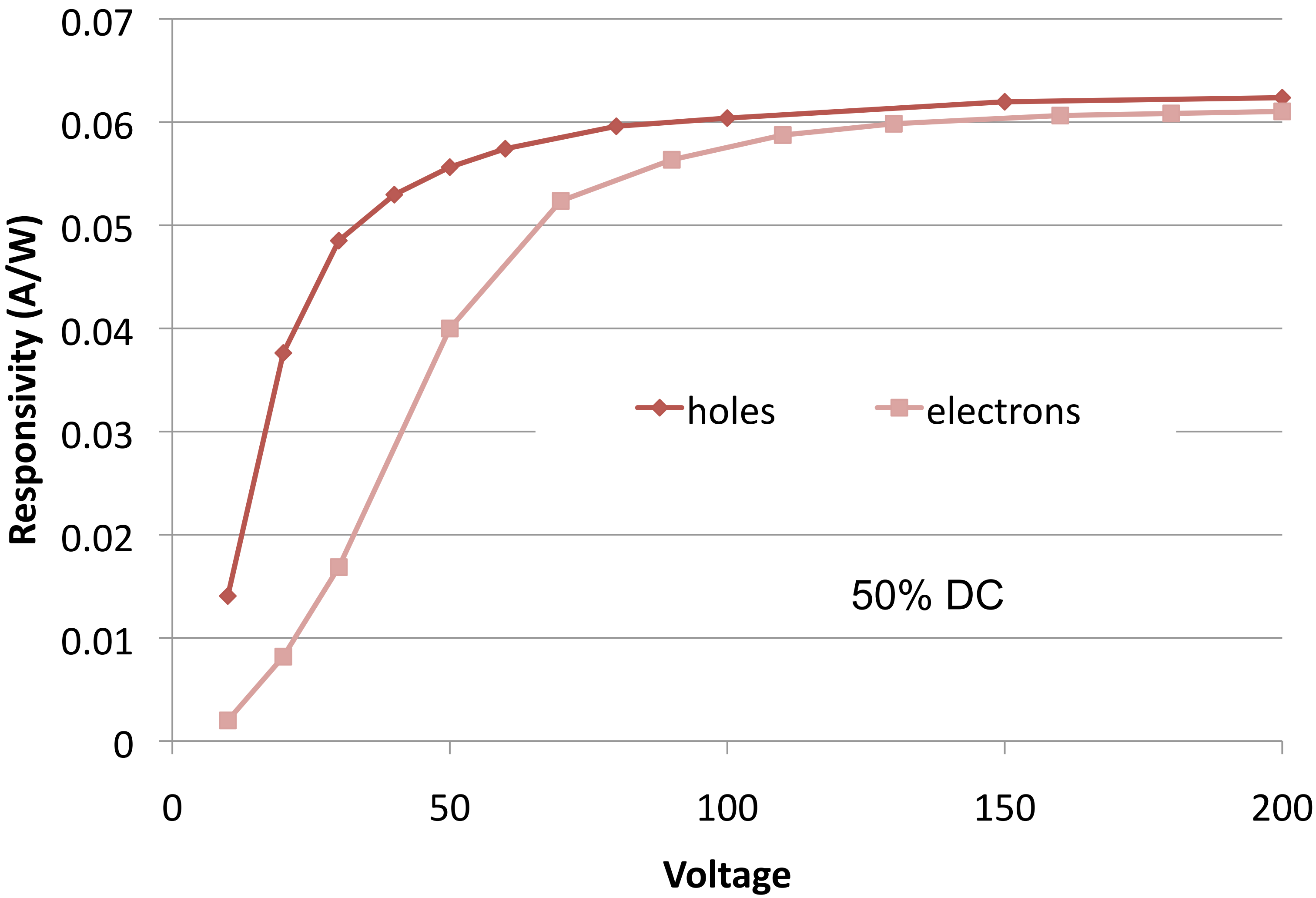
Metal-Diamond Interface

- Metals are sputtered onto diamond using mask
  -3mm diameter on center of a 4x4 square diamond
- Typical contact in industry is Ti-Pt-Au (50/50/500nm)
- We use Ti-Pt, (15/25nm), also Mo, Nb, Al and Cu
- All contacts are blocking as deposited
- For carbide-forming metals (Ti, Mo, Nb), ohmic contacts have been generated via thermal anneal
- Transition to carbide has been monitored by x-ray diffraction at X20C
- Ohmic contacts do not rely on tunneling to extract charge – should avoid charge pile-up in amplifier
- Carbides have good adhesion and thermal properties

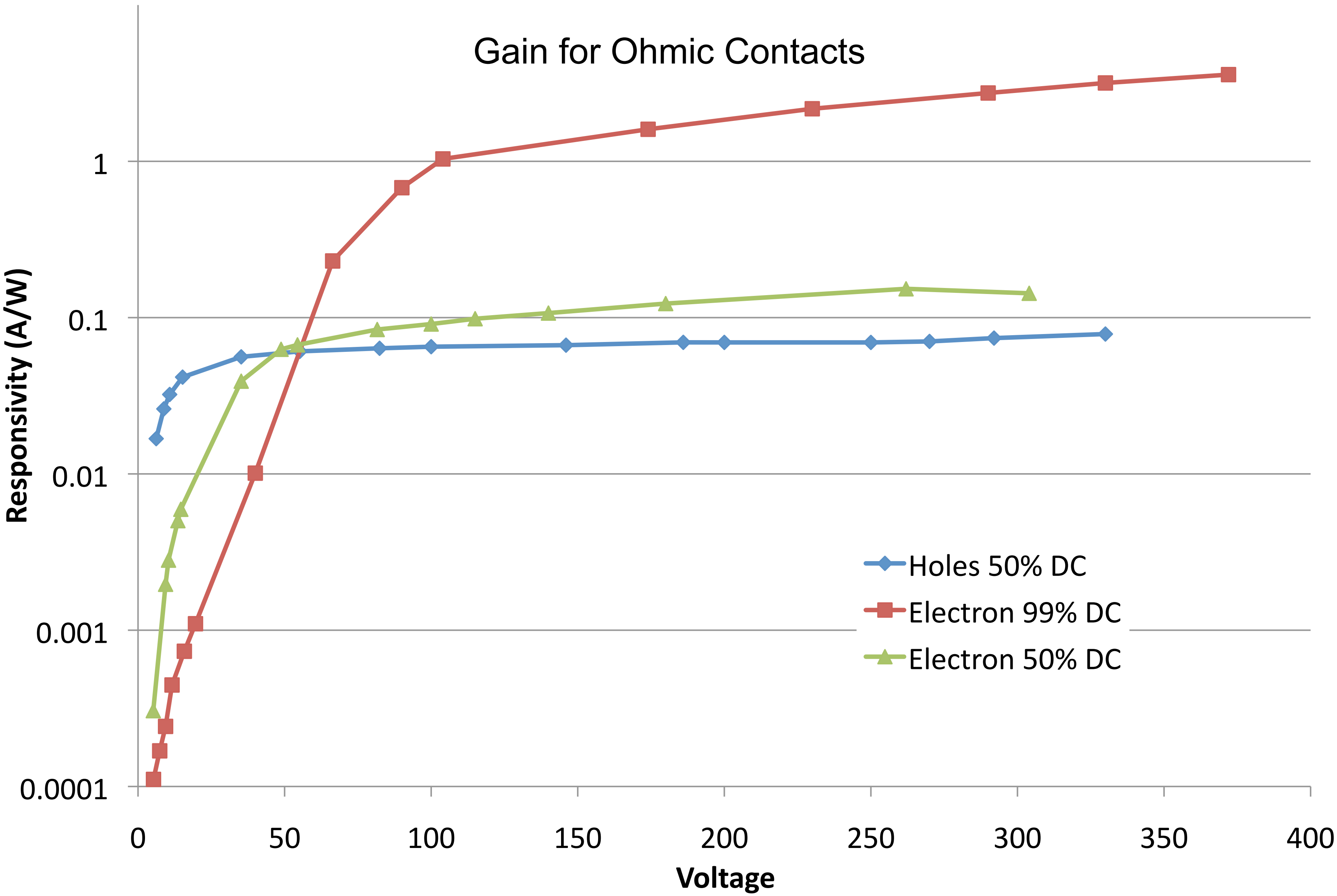
Mo -> Mo_2C


3C/s oven ramp
Two Theta (deg)
38
40
42
44
46
48
50
52
pk04
bkg
pk02
pk03
pk01
100
200
300
400
500
600
700
800
900
1000
Temperature (C)
max I = 58710.9753
min I = 46562.6786

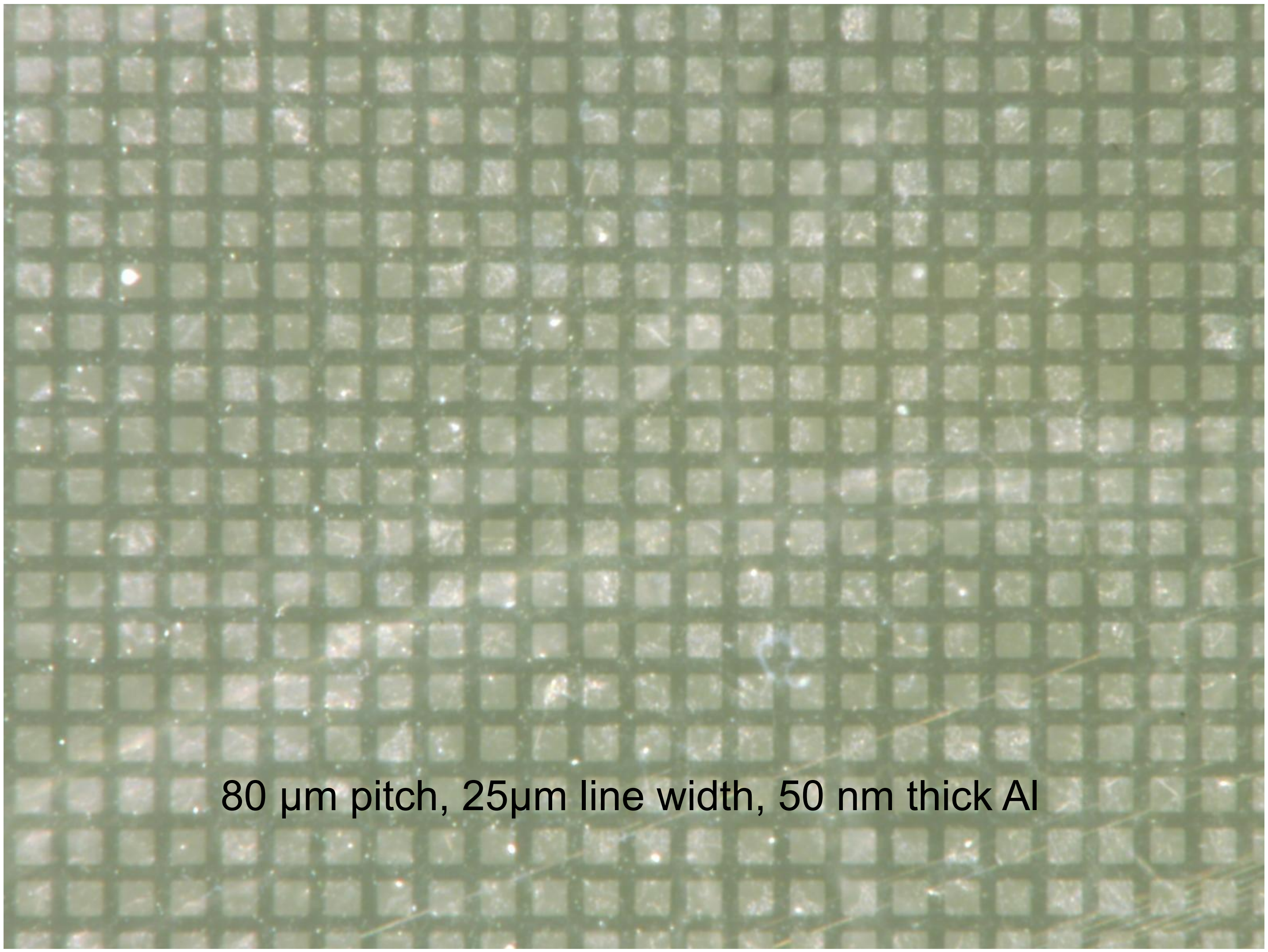
Responsivity vs Voltage (Mo, 1keV)



Responsivity (Mo_2C, post anneal, 1keV)



Lithographic Pattering of Contacts



Conclusions & Thoughts

- Unnannealed contacts are blocking in nature
- Carbide contacts become ohmic
- Model of responsivity well predicts results for wide range of photon energies
- Ohmic contacts on both sides enable photoconductive gain for electrons, suggesting electron trapping
- **Holes are the majority carrier!**
- A single ohmic contact does not allow gain => no "additional current" from hydrogenated diamonds
- Gain is not spatially uniform, suggesting that electron trapping may be related to defects

Conclusions & Thoughts

- X-ray topography suggests defects are most common near edges, where gain is highest
- Trapped electrons can be cleaned, preventing gain
- 0.1 MV/m is sufficient to collect all holes in diamond 0.5 mm thick
- 30 mA current demonstrated in 1.6 mm diameter spot => **1.5A/cm^2**
- Response is fast enough to resolve ring for 100V bias
- Significant synergy between detector and amplifier applications
- Measurement provide material data relevant to Monte Carlo modeling of amplifier (W, mobility, Charge collection distance for electrons and holes)

Thanks for your attention!

- Thanks to **Jeff Keister**, Elaine DiMasi, Jen Bohon, Jean Jordan-Sweet, Triveni Rao, John Walsh, Bill Smith
- C-AD Diamond Team: Ilan Ben-Zvi, Andrew Burrill, Qiong Wu, Xiangyun Chang, David Pate
- Beamlines: U2A, U2B, U3C, U7A, X3B, X6B, X8A, X16C, X19C, X20A&C, X28C